

# The Nuclear Effects in polarized proton-deuteron Drell-Yan processes

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## Abstract

*The longitudinally polarized Drell-Yan process is one of most powerful tools to probe the structure of hadrons. By means of the recent formalism of the polarized proton-deuteron(pd) Drell-Yan ,we calculate the ratio of the proton-deuteron Drell-Yan cross section to the proton-proton(pp) one  $\Delta\sigma_{pd}/2\Delta\sigma_{pp}$  in the polarized case. The theoretical results can be compared with future experimental data to confirm the nuclear effect due to the six-quark cluster in deuteron .*

Keywords: nuclear effect, deuteron ,quark cluster ,Drell-Yan.

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## 1. Introduction

One of the most active areas of research in nuclear and particle physics during last several decades is the study of quark and gluon distributions in the nucleons and nuclei. Several major surprises were discovered in Deep-Inelastic Scattering (DIS) experiments which profoundly changed our views of the partonic substructure of hadrons <sup>[1]</sup>. The unpolarized DIS can give accurate measurements of structure functions  $F_1(x, Q^2)$  and  $F_2(x, Q^2)$ , which depend on  $x$ , the fractional momentum carried by the struck parton, and  $Q^2$ , the four-momentum transfer squared of the

exchanged virtual photon. In the early 1980's the European Muon Collaboration (EMC)<sup>[2]</sup> found in muon DIS provided the first unambiguous evidence that the structure functions in nuclei are significantly different from those in free nucleons. This phenomenon is well-known as the EMC effect; which implies that the quark distributions are different for a bound and a free nucleon.

The  $F_1$  and  $F_2$  structure functions are sensitive to the helicity-averaged parton distributions. Recent improvements in polarized lepton beams and targets have made it possible to make increasingly accurate measurements of two additional structure functions  $g_1(x, Q^2)$  and  $g_2(x, Q^2)$ , which depend on the difference in parton distributions with helicity either aligned or anti-aligned with the spin of the parent particles<sup>[3]</sup>. In the naive quark-parton model ( $QPM$ ), the nucleon is composed of quarks which have no orbital angular momentum, and there are no polarized gluons present. In this simple picture, the unpolarized structure function  $F_1(x, Q^2)$  and polarized structure function  $g_1(x, Q^2)$  can be simply expressed as the charge weighed sum and difference between momentum distributions for quark helicities aligned paralleled ( $q^\uparrow$ ) and anti-paralleled ( $q^\downarrow$ ) to the longitudinally polarized nucleon:

$$F_1(x, Q^2) = \frac{1}{2} \sum_i e_i^2 [q_i^\uparrow(x, Q^2) + q_i^\downarrow(x, Q^2)], \quad (1)$$

$$g_1(x, Q^2) = \frac{1}{2} \sum_i e_i^2 [q_i^\uparrow(x, Q^2) - q_i^\downarrow(x, Q^2)] \equiv \frac{1}{2} \sum_i e_i \Delta q_i(x, Q^2). \quad (2)$$

The charge of quark flavor u, d, and s is denoted by  $e_i$ , and  $q_i^{\uparrow(\downarrow)}(x, Q^2)$  are the quark plus antiquark momentum distribution.

In 1987, the EMC reported results from a polarized muon-proton scattering experiment at CERN which puzzled the particle and nuclear physics communities. Contrary to the prediction of the naive quark model, the EMC found the little of

the proton spin seemed to be carried by the spins of the quarks (the so-called "spin crisis")<sup>[4]</sup>. Subsequent precision measurements are consistent with the original experimental results, but the theoretical interpretation has become more complex. It is now believed that in addition to the quarks, the orbital angular momentum and gluons may contribute significantly to the proton's spin. The polarized structure functions are interesting not only in opening a new degree of freedom with which to explore the detailed structure of the nucleon, but also for making a precise test of QCD via Bjorken sum rule which is a strict QCD prediction<sup>[5]</sup>.

The production of lepton pairs in hadron collisions, the Drell-Yan process <sup>[6]</sup> is also one of most powerful tools to probe the structure of the nucleons and nuclei. Its parton model interpretation is straightforward — the process is induced by the annihilation of a quark-antiquark pair into a virtual photon which subsequently decays into a lepton pair. The Drell-Yan process in proton-proton or proton-nucleus collisions therefore provides a direct probe of the quark distribution in the nucleon and nuclei. It is further natural to expect that a measurement of the Drell-Yan cross section in polarized proton-nucleon(nuclei) collision will yield information on the polarized quark distribution in the nucleons (nuclei), which is an alternative method to the DIS.

It has been commonly considered that the nuclear effects in deuteron are neglected, and its structure functions is regarded as the sum of the structure functions of the proton and neutron. However, Gomez et. al <sup>[7]</sup> found that the deuteron has a significant EMC effect. In addition, the E665 experimental result <sup>[8]</sup> suggests the presence of nuclear shadowing effects in deuteron. The analysis by Epele et al<sup>[9]</sup> also shows a significant nuclear effects due to the composite nature of the deuteron.

Since the experimental discovery of the EMC effect, many theoretical models

have been put forward to explain it<sup>[10]</sup>. The work by Lassila and Sukhatme<sup>[11]</sup> shows that the quark cluster model (QCM) can give a good unified explanation for the experimental data of the nuclear effects in whole  $x$  region. Spin-dependent effects in the QCM of the deuteron and  $^3He$  were investigated by Benesh and Vary<sup>[12]</sup>. But there were no detailed 6-quark clusters quark distribution by them. Several years ago, Brodsky, Burkardt and Schmidt provided a reasonable description of the spin-dependent quark distributions of the nucleon in a pQCD based model<sup>[13]</sup>. This analysis have been extended to the description of the spin-dependent quark distributions in a 6-quark cluster<sup>[14]</sup>. In previous work<sup>[15]</sup>, by means of the polarized quark distributions in a 6-quark cluster, the nuclear effects on polarized structure function in deuteron have been investigated. It is found that the calculated results with nuclear effects can better fit the SLAC E155 experimental data<sup>[16]</sup> than that without nuclear effects. In order to further investigate the nuclear effects in deuteron, an alternative way is given by combining the pd Drell-Yan data with the pp data in the polarized case.

## 2. Theoretical Scheme

Recently, the formalism of the polarized pd Drell-Yan processes had been available. A theoretical formalism had been completed for the longitudinally polarized pd Drell-Yan processes<sup>[17,18]</sup>. Taking advantage of the formalism, the nuclear-effects in deuteron can be discussed by measuring the ratio of the polarized pd Drell-Yan cross section to the polarized pp one  $\Delta\sigma_{pd}/2\Delta\sigma_{pp}$ . In the Ref.[17], the difference between the longitudinally-polarized pd cross section is given by

$$\Delta\sigma_{pd} = \sigma(\uparrow_L, -1_L) - \sigma(\uparrow_L, +1_L) \propto -\frac{1}{4}[2V_{0,0}^{LL} + (\frac{1}{3} - \cos^2 \theta)V_{2,0}^{LL}], \quad (3)$$

where the subscripts of  $\uparrow_L, +1_L$ , and  $-1_L$  indicate the longitudinal polarization ,

$\sigma(pol_p, pol_d)$  indicates the cross section with the proton polarization  $pol_p$  and the deuteron one  $pol_d$ . The longitudinally polarized structure functions  $V_{0,0}^{LL}$  and  $V_{2,0}^{LL}$  are defined in Ref.[17]. The subscripts  $l$  and  $m$  of the expression  $V_{l,m}^{LL}$  indicate that it is obtained by the integration  $\int d\Omega Y_{lm} \Delta\sigma_{pd}$ , and the superscript LL means that proton and deuteron are both longitudinally polarized. The  $\theta$  is the polar angle of the final lepton  $\mu^+$ . A parton model should be used for discussing relations between the structure functions and polarized parton distributions. In the following, we employ the expression which is obtained by integrating the cross section over the virtual-photon transverse momentum  $Q_T$ . According to Ref.[18], it is given by

$$\Delta\sigma_{pd} \propto \sum_f e_f^2 [\Delta q_f(x_1) \Delta \bar{q}_f^d(x_2) + \Delta \bar{q}_f(x_1) \Delta q_f^d(x_2)], \quad (4)$$

where  $\Delta q_f(\Delta q_f^d)$  and  $\Delta \bar{q}_f(\Delta \bar{q}_f^d)$  are the longitudinally-polarized quark and anti-quark distributions function in the proton(deuteron). The subscript  $f$  indicates quark flavor, and  $e_f$  is the corresponding quark charge.  $x_1$  and  $x_2$  are the momentum fractions of proton (deuteron) carried by the quark or anti-quark.

If we disregard the nuclear effects in deuteron and assume isospin symmetry, the polarized quark distribution functions in deuteron can be expressed as

$$\begin{aligned} \Delta u^d &= \Delta u + \Delta d, \Delta d^d = \Delta d + \Delta u, \Delta s^d = 2\Delta s, \\ \Delta \bar{u}^d &= \Delta \bar{u} + \Delta \bar{d}, \Delta \bar{d}^d = \Delta \bar{d} + \Delta \bar{u}, \Delta \bar{s}^d = 2\Delta \bar{s}, \end{aligned} \quad (5)$$

where  $\Delta q$  ( $\Delta \bar{q}$ ) is quark (anti-quark) polarization distribution function in proton. Similarly, the pp Drell-Yan cross section are given by simply substituting  $q^d(\bar{q}^d)$  with  $q(\bar{q})$ . Therefore, the ratio of the pd cross section to the pp one is then obtained as,

$$R_{pd} = \frac{\Delta\sigma_{pd}}{2\Delta\sigma_{pp}} = \frac{\sum_f e_f^2 [\Delta q_f(x_1) \Delta \bar{q}_f^d(x_2) + \Delta \bar{q}_f(x_1) \Delta q_f^d(x_2)]}{2 \sum_f e_f^2 [\Delta q_f(x_1) \Delta \bar{q}_f(x_2) + \Delta \bar{q}_f(x_1) \Delta q_f(x_2)]} \quad (6)$$

The behavior of  $R_{pd}$  at two  $x_F$  extreme limits have been analyzed by Kumano and Miyama<sup>[19]</sup>. If two extreme limits ( $x_F = x_1 - x_2 \rightarrow \pm 1$ ) are taken in Eq.(6) with the assumption  $\Delta u_v(x \rightarrow 1) \gg \Delta d_v(x \rightarrow 1)$ <sup>[13,20]</sup>, the ratio becomes

$$R_{pd}(x_F \rightarrow +1) = \frac{1}{2} \left[ 1 + \frac{\Delta \bar{d}(x_2)}{\Delta \bar{u}(x_2)} \right]_{x_2 \rightarrow 0} \quad (7)$$

$$R_{pd}(x_F \rightarrow -1) = \frac{1}{2} \left[ 1 + \frac{\Delta \bar{d}(x_1)}{4\Delta \bar{u}(x_1)} \right]_{x_1 \rightarrow 0} \quad (8)$$

It is found that the flavor-asymmetric distribution  $\Delta \bar{u} - \Delta \bar{d}$  can be extracted by finding the deviation from 1 at  $x_F \rightarrow \pm 1$  or from 5/8 at  $x_F \rightarrow -1$ . However,  $R_{pd}$  in other  $x_F$  regions are not so promising in the flavor asymmetry, and can be used to find the x dependence of the polarized quark distributions function in deuteron so that the nuclear effects in deuteron can be shed light on .

Now let's turn to investigate the nuclear Effects in polarized proton-deuteron Drell-Yan processes. In the quark cluster model, the presence of 6-quark cluster is used to understand the nuclear effects in deuteron. Therefore, when we take account of the nuclear effects in deuteron and employ isospin symmetry, the polarized quark distribution function in deuteron can be written as

$$\begin{aligned} \Delta u^d &= p_3(\Delta u + \Delta d) + p_6 \Delta u^6, \Delta d^d = p_3(\Delta d + \Delta u) + p_6 \Delta d^6, \\ \Delta s^d &= 2p_3 \Delta s + p_6 \Delta s^6, \Delta \bar{u}^d = p_3(\Delta \bar{u} + \Delta \bar{d}) + p_6 \Delta \bar{u}^6, \\ \Delta \bar{d}^d &= p_3(\Delta \bar{d} + \Delta \bar{u}) + p_6 \Delta \bar{d}^6, \Delta \bar{s}^d = 2p_3 \Delta \bar{s} + p_6 \Delta \bar{s}^6, \end{aligned} \quad (9)$$

where  $\Delta q^6$  ( $\Delta \bar{q}^6$ ) is quark ( anti-quark) polarization distribution function in deuteron ,  $p_3 = [(p_s - p_{6s}) - \frac{1}{2}(p_d - p_{6d})]$  is the possibilities for creating 3-quark cluster ,  $p_s = 0.957$  and  $p_d = 0.043$  denote the probabilities for finding the deuteron in an s or d wave, respectively.  $p_6 = p_{6s} + p_{6d}$ , in which  $p_{6s} = 0.047$  and  $p_{6d} = 0.007$

calculated by Benesh and Bary<sup>[12]</sup> are the probabilities for creating a 6-quark cluster in the s- and d-states , denote the possibilities for creating 6-quark cluster in deuteron .

### 3. Results and Discussions

With all ingredient sets as given above, we can numerically calculate the ratio of the polarized pd Drell-Yan cross section to the pp one  $\Delta\sigma_{pd}/2\Delta\sigma_{pp}$  with nuclear effects and without nuclear effects in deuteron. In our calculation, the polarized parton distribution functions for proton are taken from the new version of the LSS(Lead-Sidorov-Stamenev) leading-order(LO) parameterization<sup>[21]</sup>. In Fig.1, the theoretical results are given with taking center-of-mass energy  $\sqrt{s} = 50\text{GeV}$  and dimuon mass  $M_{\mu\mu} = 5\text{Gev}$ . The solid curve denotes the  $R_{pd}$  with the nuclear effects due to 6-quark clusters in deuteron , the dashed curve corresponds to not considering the 6-quark clusters. In addition, the Drell-Yan cross section ratio  $R_{pd}$  is calculated at  $\sqrt{s} = 200\text{GeV}$  and  $M_{\mu\mu} = 5\text{GeV}$  , the results are shown in Fig.2. It is obvious that the nuclear effects in deuteron become more significant at higher center-of-mass energy and large  $x_F$ . Because the difference between  $R_{pd}$  with nuclear effects and without nuclear effects in the range  $x_F > 0.08$  is larger at higher center-of-mass energy, this makes it possible to further confirm the nuclear effects in deuteron .

In summary , we have investigated the longitudinally polarized Drell-Yan cross section ratio  $\Delta\sigma_{pd}/2\Delta\sigma_{pp}$  by means of the recent formalism for the polarized pd Drell-Yan processes . It is shown that the information on the nuclear effects in deuteron can be extracted in the future experiment. Although there is not experiments for the polarized pd Drell-Yan at this stage , we suggest precise experimental

research on this reaction at FNAL ,HEAR ,and RICH ,which makes us good understanding the unclear effects in deuteron .

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#### Figure caption

Fig.1 The Drell-Yan cross section ratio  $R_{pd}$  with  $\sqrt{s} = 50\text{GeV}$  and  $M_{\mu\mu} = 5\text{GeV}$ . The solid curve corresponds to including contributions of the 6-quark clusters, i. e. nuclear effects. The dashed curve denotes the results without 6-quark clusters in deuteron.

Fig.2 The Drell-Yan cross section ratio  $R_{pd}$  with  $\sqrt{s} = 200\text{GeV}$  and  $M_{\mu\mu} = 5\text{GeV}$ . The comments are the same as Fig. 1.